Increase of monoterpene emissions from a pine plantation as a result of mechanical disturbances

Gunnar W. Schade[1] and Allen H. Goldstein

Department of Ecosystem Sciences, Policy and Management (ESPM), Division of Environmental Sciences, University of California, Berkeley, California, USA

Received 20 August 2002; revised 21 November 2002; accepted 3 February 2003; published 5 April 2003.

[1] Mixing ratios and emission rates of monoterpenes were measured above a ponderosa pine plantation in the Sierra Nevada mountains before, during and after a pre-commercial thinning in spring 2000. The thinning removed and left onsite approximately one half of the plantations biomass. Monoterpene fluxes increased tenfold during the thinning and pinene mixing ratios in excess of 3 ppb were observed, possibly altering regional atmospheric chemistry. The increase was mostly because of higher basal emission rates, but small changes in the temperature-dependence were also found. Using an emission-model based on these responses, the additional monoterpene emissions due to the thinning were estimated to increase emissions by a factor of forty, and yearly emissions by a factor of five. Using US tables of absolute timber removal and on site residue volumes from logging and thinning activities, we calculate that current US monoterpene emissions may be underestimated by several percent. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0322 Constituent sources and sinks; 0365 Troposphere—composition and chemistry. **Citation:** Schade, G. W., and A. H. Goldstein, Increase of monoterpene emissions from a pine plantation as a result of mechanical disturbances, *Geophys. Res. Lett.*, *30*(7), 1380, doi:10.1029/2002GL016138, 2003.

1. Introduction

[2] Biogenic monoterpene emissions contribute to photochemical ozone formation [*Chameides et al.*, 1988] and influence the atmosphere's oxidative capacity, while their oxidation products can be a significant factor in secondary aerosol formation [*Andreae and Crutzen*, 1996], in particular in coniferous forest areas [*Kavouras et al.*, 1999]. Models of monoterpene emission rates from forests presume emissions to be driven by ambient light and temperature [*Ciccioli et al.*, 1997; *Staudt and Bertin*, 1998], or presume emissions to be driven by temperature only [*Tingey et al.*, 1980; *Janson*, 1993; *Guenther et al.*, 1991, 1993, 1995], using the formula

$$F = F_{ref} \times \exp\left[\beta \times \left(T - T_{ref}\right)\right] \quad (1)$$

where F is the flux (mg C m^{-2} h^{-1}), T is temperature, β is the temperature-dependence factor, T_{ref} is a reference temperature typically chosen to be 30°C, and F_{ref} the flux at that temperature. Generally, only emissions from green leaves and needles are considered to be significant. For US forests, monoterpene emissions are routinely calculated with the BEIS2 model, which considers green leaf biomass and leaf temperature as input values [*Geron et al.*, 1994; *Guenther et al.*, 2000]. However, several studies have shown that high ambient humidity levels or mechanical disturbances such as touching, rain or herbivory can enhance emissions [*Street et al.*, 1997; *Litvak and Monson*, 1998; *Schade et al.*, 1999, and references therein]. While intact branches and trunks are commonly not counted as significant monoterpene emission surfaces, the intense "coniferous" or "pine" smell emanating from sap during softwood cutting is well known. Hence, it appears likely that a significant amount of them is released during logging and thinning operations in the world's forests.

[3] Here, we present data on monoterpene fluxes from in-situ field measurements above a ponderosa pine plantation before, during, and after a routine thinning procedure in spring 2000, which masticated and left on site two thirds of the plantation's trees. We show both the absolute effect on emissions as well as its temperature dependence. We then use a model fit to calculate total additional monoterpene emissions, compare to emissions that would have occurred without the thinning, and estimate additional US monoterpene emissions from tabulated data on logging and thinning activities.

2. Flux Measurements and Thinning Procedure

[4] Monoterpene flux was measured at one-hour intervals above a ponderosa pine (*Pinus ponderosa* L.) plantation adjacent to the Blodgett Forest Research Station on the western slope of the Sierra Nevada Mountains of California (38°53′ 42.9″ N, 120° 37′ 57.9″ W, 1315 m elevation). The measurement setup and site are described extensively in *Schade and Goldstein* [2001] and *Goldstein et al.* [2000]. Monoterpene mixing ratios and fluxes were measured from approximately 6 m above the average tree height with a Relaxed-Eddy-Accumulation (REA) GC-FID system, using preconcentration on chilled Silcosteel© microtraps packed with carbon-based adsorbents [*Lamanna and Goldstein*, 1999]. Approximately 120 mL of air was sub-sampled at 15 mL min^{-1} through the fast-acting REA valves out of the 10 L min^{-1} main sample flow. The system was calibrated by diluting ppm-level monoterpene standards (α-pinene, Δ-3-carene, and β-pinene in UHP N_2 (Scott-Marrin Inc., Riverside, CA)) into the main flow every 10th sample. The mean minimum detectable flux at the 90% confidence level was approximately 0.04 mg C m^{-2} h^{-1}.

[1]Now at Institute for Environmental Physics (IUP), University of Bremen, Bremen, Germany.

0094-8276/03/2002GL016138$05.00

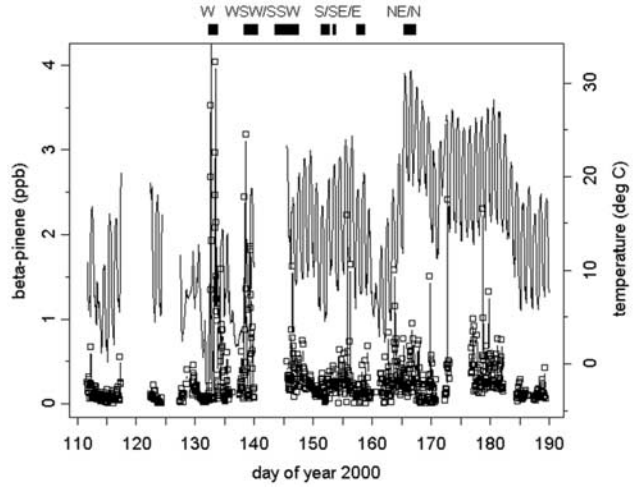

Figure 1. Variation of β-pinene mixing ratios and ambient temperature during spring 2000. The bars and letters on top show the times of actual thinning, and its approximate direction from the flux tower.

[5] Pre-commercial thinning is a routine procedure in plantation management carried out to reduce stand density, improve forest health, and optimize tree growth, as generally the tallest and healthiest trees are retained [*Nyland*, 2002; *Savill et al.*, 1997] thereby minimizing inter-tree competition for resources such as light and water. Thinning started on 11 May and ended on 15 June 2000. It was carried out as a spacing thinning [*Nyland*, 2002] with a single masticator [*California Department of Forestry and fire Protection* (*CDF*), 2002] and proceeded counterclockwise around the flux tower, starting in the West-South-West (WSW), which also is the main daytime wind direction. Mastication, or ''chewing-up'', is the process of mechanically breaking up top-to-bottom unwanted trees [*CDF*, 2002], and is becoming a more widespread method of thinning in the US. By definition, trees cut in pre-commercial thinning in the US are almost universally left on site. For commercial thinning and logging operations, the fate of debris (tops, limbs, all green parts) depends in large part on 1) whether the objective is to minimize fuel loading or retain nutrients, and 2) the harvest systems employed. Where mechanized whole tree systems are used, tops and limbs are removed from the stand but may remain on the landing site until burned, chipped, or redistributed into the stand. These systems are very common in the Southeast, the interior West, and for smaller trees on flatter terrain in the West of the US. Mechanized cut-to-length systems leave the debris within the stand. They are much less common in the US than in Europe and Scandinavia, but are becoming more widespread, especially in the Midwest and in thinning in the Pacific Northwest. In mountainous terrain, such as the Sierra Nevada, where chainsaws are used to fell and delimb larger trees, all debris stays on site. It is that debris that is most relevant to continued monoterpene emissions.

[6] Thinning at the Blodgett site reduced the green leaf biomass from ~320 g m^{-2} to ~150 g m^{-2}, and created branch and stem debris of 400–500 g m^{-2} (dry weight based on allometric relationships [*Xu*, 2000]). In a young stand like ours, a higher leaf and branch biomass is maintained as compared to stem-wood biomass. For trees at logging ages, such as 60 years and older, branch and leaf biomass accounts for only one fifth to at most one third of stem-wood biomass.

3. Results and Discussion

[7] Ambient mixing ratios for all the monoterpenes measured increased dramatically with the onset of thinning despite low ambient temperatures. Figure 1 shows β-pinene mixing ratios along with ambient temperatures and the mastication schedule and rough location. The highest mixing ratios were observed while thinning occurred in close proximity to the flux tower in the main flux footprint area during the initial days (days 133–135), and during a heatwave at the end of the thinning schedule (days 165–167). Monoterpene fluxes were highly variable and not available during the complete period. We have aggregated the available data into several phases shown as an example of trimmed mean diurnal flux cycles of α-pinene in Figure 2: Pre-mastication, I (before 11 May, day 132; 3–9 valid measurements per hour (h^{-1})), during mastication, II (days 132–154; 5–14 h^{-1}), post-mastication, III (days 155–170; 7–14 h^{-1}), mid-summer mean fluxes, IV (days 190–245; 21–35 h^{-1}), and a late fall period for comparison. This grouping takes into account that thinning in the SW fetch of the flux tower was essentially completed half way into the thinning period. Obviously, thinning had a profound and lasting effect upon monoterpene emissions. Aggregating α-pinene emissions into 2-degree temperature intervals, shown in Figure 3, demonstrates that the bulk of the flux increase was due to an increase in basal emissions in all cases, while small changes were also detected in the temperature-response of emissions during and after the thinning. A complete listing of emission parameters for the three main monoterpenes, representing over 90% of measured monoterpenes, through the first four phases listed above, and the summer 1999 reference is given in Table 1. Compared to our flux measurements from the undisturbed plantation in 1998 and 1999 [*Schade et al.*, 1999; *Schade and Goldstein*,

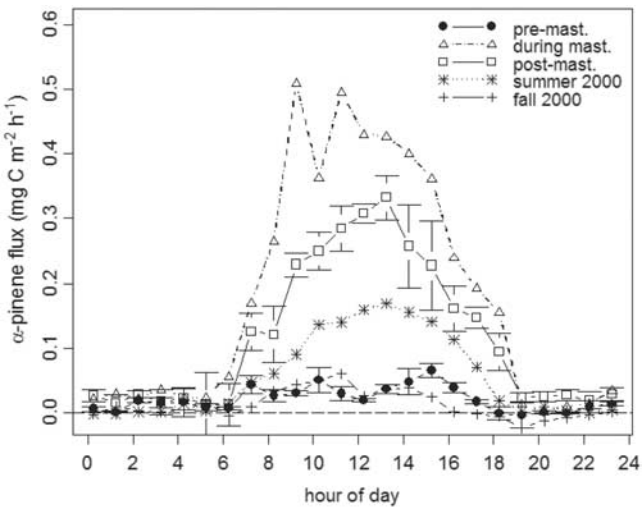

Figure 2. Trimmed mean α-pinene fluxes during phases I–IV, and during fall 2000. Error bars are standard errors and were limited to two data sets for readability.

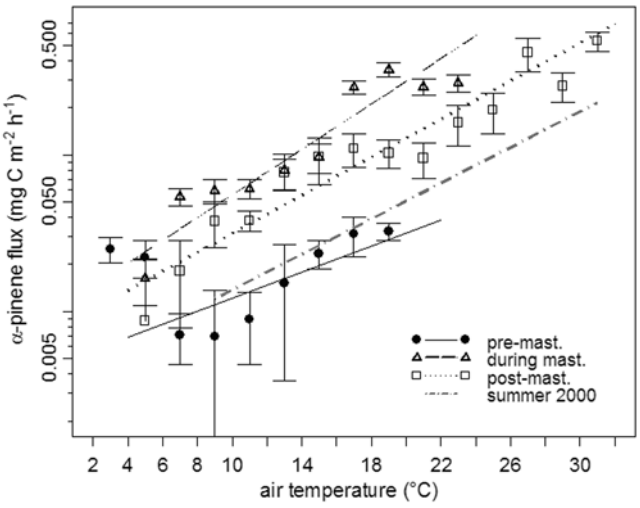

Figure 3. Temperature response of daytime α-pinene fluxes for the different emission phases. Error bars are standard errors as described in Table 1. High fluxes at lower temperatures were often associated with moisture effects [*Schade et al.*, 1999].

2001], Δ-3-carene fluxes increased more strongly than β-pinene or α-pinene fluxes. That is consistent with Δ-3-carene as the dominant ponderosa pine wood monoterpene in this area [*Smith*, 2000]. The systematic β-factor decrease from phase II to III, though within the measurements error, may point to a source with a smaller monoterpene resistance to emission during phase III, possibly woody debris dominating over ''green'' leaf debris at lower temperatures.

[8] Except for Δ-3-carene, mean summer fluxes in 1999 and 2000 were of comparable magnitude as the new needle development in 2000 had replaced most of the thinned needle biomass by the end of August, as common for thinning in plantations of this age [*Savill et al.*, 1997]. Hence, the removed biomass now present as litter throughout the plantation seemed to add only a small pinene flux to the one coming from live green needles two months after the thinning procedure. This apparently rapid loss of monoterpenes from debris is likely connected to the increased radiation levels, and therefore higher temperatures, at the ground after the tree removal. The Δ-3-carene flux, however, continued to be higher, possibly a result of its continued emanation from woody debris.

[9] Based on the model fits listed in Table 1, we calculated the amount of ''additional'' α-pinene, β-pinene, and Δ-3-carene emissions, between days 132 and 170 (18 June), considering that non-disturbed emissions would have followed the pre-thinning temperature model, because the main new needle elongation growth occurred in late June and July 2000. We calculated that monoterpene emissions were enhanced 40 times (range 22–94) during the thinning period (phases II and III). Comparing this to the summer 2000 emissions (phase IV), calculated in the same manner, we found that monoterpene emissions were approximately ten times higher (range 5–23) due to the thinning procedure. On an annual basis, we extrapolated that the thinning procedure created five times (range 3–12) as much monoterpene emissions to the atmosphere than would have occurred without the thinning.

4. Implications

[10] To estimate the amount of potential additional emissions of monoterpenes from the forest management procedures of thinning and logging, we refer to the newest US forestry statistics (Renewable Resources Planning Act Assessment 2002 (RPA), Forest Resources of the United States, Draft Tables, available at http://www. ncrs. fs. fed. us/4801/FIADB/index. htm, hereinafter referred to as RPA, 2002) and base our calculations both on the area logged and the debris created. Annually, approximately 2% by volume of inventoried softwood timber is ''removed'' (i.e. logged or thinned) from US timberland (total: $\sim 15 \times 10^9$ m^3; removed: $\sim 0.34 \times 10^9$ m^3). If we assume that this volume-ratio can be transformed into an area-ratio without a significant bias, we find that approximately 23×10^9 m^2 or 1%–1.5% of the total forest area emitting significant amounts of monoterpenes is logged or thinned annually by summing the tabulated timberland areas of the following ''forest type groups'' (RPA, 2002): *Pinus contorta*, *edulis*, *elliotti*, *echinata*, *ponderosa*, *strobus*, and *taeda*, *Picea* and *Abies* spp., *Pseudotsuga menziesii*, *Liquidambar styraciflua*, *Carya* spp., and *Acer* spp. These groups together account for more than 80% of US monoterpene emissions [*Geron et al.*, 2000]. However, as the non-pine species from this list likely emit less monoterpenes from their woody debris than the pines, our estimate is a high estimate, with pine species likely contributing more than half to the emissions ($\sim 13 \times 10^9$ m^2 logged area).

[11] The aerial logging estimate of around 1%–2% of the total is consistent with an average life cycle for conifers of less than 100 years until logging, but does not take into account that other management practices, such as thinning, occur typically two times before that in plantations, which account for a fast-growing area of US timberland (2000: ~8%). We may therefore use the upper value for a first extrapolation. Based on the relative area calculated above, we estimate that current monoterpene emission models for

Table 1. Basal Emission Rate (F_{ref}) at 30°C (in mg C m^{-2} h^{-1}) and its Ranges, and β-factor (in K^{-1}) With Standard Errors, for the Phases Described in the Text and the Main Monoterpenes Emitted

	α-pinene			β-pinene			Δ-3-carene		
phase	F_{ref}	F_{ref} range[a]	β[a]	F_{ref}	F_{ref} range[a]	β[a]	F_{ref}	F_{ref} range[a]	β[a]
I	0.08	0.05–0.13	0.095 ± 0.038	0.30	0.24–0.38	0.084 ± 0.019	0.26	0.20–0.35	0.118 ± 0.033
II	1.56	1.19–2.04	0.167 ± 0.023	4.93	4.12–5.91	0.187 ± 0.015	3.96	1.95–7.91	0.152 ± 0.065
III	0.52	0.42–0.64	0.140 ± 0.015	1.05	0.83–1.32	0.122 ± 0.015	0.27	0.18–0.41	0.094 ± 0.032
IV	0.20	0.10–0.38	0.131 ± 0.026	0.44	0.22–0.86	0.120 ± 0.027	0.46	0.31–0.69	0.117 ± 0.015
1999	0.17	0.12–0.24	0.120 ± 0.015	0.43	0.33–0.57	0.100 ± 0.012	0.20	0.08–0.52	0.140 ± 0.040

[a]Error ranges are based on variability-weighted log-linear regressions of all flux data excluding flyers.

the US [*Guenther et al.*, 2000] may not account for up to 8% of additional emissions. The most significant uncertainty in this high estimate comes from the large range of possible relative emissions increases (range 3–12), not from the logged area.

[12] The second estimate is based on the additional monoterpene mass emitted from the thinning process (phases II and III), which we calculated at approximately 5.5 g C m^{-2} (range 3–13 g C m^{-2}). We assume that this mass was emitted from 600–700 g m^{-2} onsite leaf and woody debris created from the thinning, and that $9–19 \times 10^{12}$ g dry weight debris is left behind annually from logging and thinning activities in conifer forests (RPA, 2002). We calculate that $0.04–0.41 \times 10^{12}$ g C in monoterpenes, with a best estimate of 0.13×10^{12} g C, could be emitted from thinning and logging operations in the US. Comparing this to a modeled 7.5×10^{12} g C total monoterpene emissions from live vegetation [*Guenther et al.*, 2000], shows that emissions may be underestimated by 2% (range 0.5%–5.5%), consistent with the area estimate. In this case, approximately equal uncertainties are introduced from our flux data and the listed debris data and its conversion.

[13] On a global basis, monoterpene emissions could be underestimated as well due to 1. ongoing deforestation in the tropics, and 2. a rapid global increase in managed forestland, in particular in fast-growing plantations [*Food and Agricultural Organization of the United Nations* (*FAO*), 2000]. Although forest plantations currently represent only 5% of the world's forested area, they supply one third of global roundwood with a significant growth expectation in the future [*FAO*, 2000]. As at least two of the dominant plantation species - pine and eucalyptus - are high monoterpene emitters, an increase in the global forest area managed in plantations can be expected to significantly increase global monoterpene emissions as well.

[14] On a local basis, monoterpene mixing ratios and fluxes can be increased 10–30-fold during and after major disturbances, which should alter local or even regional boundary layer chemistry [*Litvak et al.*, 1999]. The main contribution to the emission's upsurge obviously comes from an increased basal emission rate, with a relatively larger contribution from the major monoterpene compound in the wood. As a consequence, the timing of thinning and logging activities could have implications for regional air quality management, likely both in terms of ozone chemistry and secondary aerosol formation.

[15] **Acknowledgments.** This work was supported by grants from the California Air Resources Board (ARB Contract Numbers 98-328, 00-732), the National Science Foundation (Award Number ATM-0119510), and the University of California Agricultural Experiment Station. We are grateful to Bruce Hartsough and Frieder Schurr for their valuable inputs on forestry practices. The authors further thank Megan McKay for her invaluable help, Dave Rambeau for carrying out and keeping a log of the mastication progress, the Blodgett Forest crew for their support, SPI for the permission to carry out this research on their property, and two anonymous reviewers for their very constructive comments.

References

Andreae, M. O., and P. J. Crutzen, Atmospheric aerosols: Biogeochemical sources and role in atmospheric chemistry, *Science*, *276*, 1052–1058, 1996.

California Department of Forestry and Fire Protection (CDF), Meet the masticator, in *Spring 2002 Newsletter*, Forest Stewardship Program, Sacramento, Calif., 2002. (Available at http://ceres.ca.gov/foreststeward/html/masticator.html.)

Chameides, W. L., R. W. Lindsay, J. Richardson, and C. S. Kiang, The role of biogenic hydrocarbons in urban photochemical smog: Atlanta as a case study, *Science*, *241*, 1473–1475, 1988.

Ciccioli, P., et al., Use of the isoprene algorithm for predicting the monoterpene emission from the Mediterranean holm oak Quercus ilex L.: Performance and limits of this approach, *J. Geophys. Res.*, *102*, 23,319–23,328, 1997.

Food and Agriculture Organization of the United Nations (FAO), *State of the World's Forest 2001*, Rome, 2001.

Geron, C., A. Guenther, and T. Pierce, An improved model for estimating emissions of volatile organic compounds from forest in the eastern United States, *J. Geophys. Res.*, *99*, 12,773–12,792, 1994.

Geron, C., R. Rasmussen, R. R. Arnts, and A. Guenther, A review and synthesis of monoterpene speciation from forest in the United States, *Atmos. Environ.*, *34*, 1761–1781, 2000.

Goldstein, A. H., J. M. Frachebaud, M. R. Bauer, J. A. Panek, A. Guenther, and B. Baugh, Effects of seasonal drought stress on the carbon dioxide, water, and sensible heat fluxes above a ponderosa pine plantation in the Sierra Nevada (CA), *Agric. For. Meteorol.*, *101*, 113–129, 2000.

Guenther, A. B., R. K. Monson, and R. Fall, Isoprene and monoterpene emission rate variability—Observations with eucalyptus and emission rate algorithm development, *J. Geophys. Res.*, *96*, 10,799–10,808, 1991.

Guenther, A. B., P. R. Zimmerman, P. C. Harley, R. K. Monson, and R. Fall, Isoprene and monoterpene emission rate variability—Model evaluations and sensitivity analyses, *J. Geophys. Res.*, *98*, 12,609–12,617, 1993.

Guenther, A., et al., A global model of volatile organic compound emissions, *J. Geophys. Res.*, *100*, 8873–8892, 1995.

Guenther, A., C. Geron, T. Pierce, B. Lamb, P. Harley, and R. Fall, Natural emissions of non-methane volatile organic compounds, carbon monoxide, and oxides of nitrogen from North America, *Atmos. Environ.*, *34*, 2205–2230, 2000.

Janson, R. W., Monoterpene emissions from Scots pine and Norwegian spruce, *J. Geophys. Res.*, *98*, 2839–2850, 1993.

Kavouras, I. G., N. Mihalopoulos, and E. G. Stephanou, Formation and gas/particle partioning of monoterpene photo-oxidation products over forest, *Geophys. Res. Lett.*, *26*, 55–58, 1999.

Lamanna, M. S., and A. H. Goldstein, In-situ measurements of $C_2–C_{10}$ VOCs above a Sierra Nevada ponderosa pine plantation, *J. Geophys. Res.*, *104*, 21,247–21,262, 1999.

Litvak, M. E., and R. K. Monson, Patterns of induced and constitutive monoterpene production in conifer needles in relation to insect herbivory, *Oecologia Berlin*, *114*, 531–540, 1998.

Litvak, M. E., S. Madronich, and R. K. Monson, Herbivore-induced monoterpene emissions from coniferous forests: Potential impact on local tropospheric chemistry, *Ecol. Appl.*, *9*, 1147–1159, 1999.

Nyland, R. D., *Silviculture, Concepts and Applications*, 2nd ed., McGraw-Hill, New York, 2002.

Savill, P. S., E. Evans, D. Auclair, and J. Falck, *Plantation Silviculture in Europe*, Oxford Univ. Press, New York, 1997.

Schade, G. W., and A. H. Goldstein, Fluxes of oxygenated volatile organic compounds from a ponderosa pine plantation, *J. Geophys. Res.*, *106*, 3111–3124, 2001.

Schade, G. W., A. H. Goldstein, and M. S. Lamanna, Are monoterpene emissions influenced by humidity?, *Geophys. Res. Lett.*, *26*, 2187–2190, 1999.

Smith, R. H., Xylem monoterpenes of pines: Distribution, variation, genetics, function, *Forest Serv. General Tech. Rep. PSW-GTR-177*, U.S. Dep. of Agric., Washington, D. C., 2000.

Staudt, M., and N. Bertin, Light and temperature dependence of the emission of cyclic and acyclic monoterpenes from holm oak (*Quercus ilex L.*) leaves, *Plant Cell Environ.*, *21*, 385–395, 1998.

Street, R. A., C. N. Hewitt, and S. Mennicken, Isoprene and monoterpene emissions from a Eucalyptus plantation in Portugal, *J. Geophys. Res.*, *102*, 15,875–15,887, 1997.

Tingey, D. T., M. Manning, L. C. Grothaus, and W. F. Burns, Influence of light and temperature on monoterpene emissions rates from slash pine, *Plant Physiol.*, *65*, 797–801, 1980.

Xu, M., Ecosystem carbon measurement, modeling, and management in a young ponderosa pine plantation in northern California, Ph.D. thesis, Univ. of Calif., Berkeley, 2000.

A. H. Goldstein, ESPM, Division of Ecosystem Sciences, University of California at Berkeley, 250 Hilgard Hall, Berkeley, CA 94720, USA. (gws@iup.physik.uni-bremmen.de)

G. W. Schade, Institute for Environmental Physics (IUP), University of Bremen, NW1 28359 Bremen, Germany.